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F. Argelaguet, M. Sugimoto, and R. McMahan (Editors)

Does the Control Law Matter? Characterization and Evaluation of Control Laws for Virtual Steering Navigation

Hugo Brument[†1] Anne-Hélène Olivier[†2]Maud Marchal[†3] Ferran Argelaguet[†1]

[1]Inria, Univ. Rennes, CNRS, IRISA, France
[2]Univ Rennes, Inria, CNRS, IRISA, M2S, Rennes, France
[3]Univ. Rennes, INSA, IRISA, Inria, CNRS – France and IUF

Abstract

This paper aims to investigate the influence of the control law in virtual steering techniques, and in particular the speed update, on users' behaviour while navigating in virtual environments. To this end, we first propose to characterize existing control laws. Then, we designed a user study to evaluate the impact of the control law on users' behaviour and performance in a navigation task. Participants had to perform a virtual slalom while wearing a head-mounted display. They were following three different sinusoidal-like trajectory (with low, medium and high curvature) using a torso-steering navigation technique with three different control laws (constant, linear and adaptive). The adaptive control law, based on the biomechanics of human walking, takes into account the relation between speed and curvature. We propose a spatial and temporal analysis of the trajectories performed both in the virtual and the real environment. The results show that users' trajectories and behaviors were significantly affected by the shape of the trajectory but also by the control law. In particular, users' angular velocity was higher with constant and linear laws compared to the adaptive law. The analysis of subjective feedback suggests that these differences might result in a lower perceived physical demand and effort for the adaptive control law. The paper concludes discussing the potential applications of such results to improve the design and evaluation of navigation control laws.

CCS Concepts

• ***Human-centered computing*** $\rightarrow$ ***Virtual reality; User studies;***

1. Introduction

Navigation is a fundamental interaction in Virtual Reality (VR) that enables users to update their viewpoint in order to explore the Virtual Environment (VE). While real walking has been acknowledged to be the most ecological approach to navigate in a VE as it better matches real locomotion tasks [NSBK15, RVB13, UAW*99], it also requires a large physical workspace that is generally not available in most VR setups. Since the beginning of VR systems, alternative navigation techniques have been explored to enable users to navigate infinitely regardless of the size of the physical workspace. Among the wide number of solutions that have been proposed for virtual navigation in VR [LKMP17], some encourage users' physical movement (e.g. redirected walking or walking-in-place), while others require minimal users' motion, such as virtual steering techniques or teleport-based. When designing navigation techniques, three major components [LKMP17] can be identified: (1) the direction/target selection, (2) the input conditions and (3) the speed/acceleration selection. The evaluations of navigation techniques [BH99, BKH98, BJH01] mostly focus on the two first components without considering the last one, thereafter referred as the control law. Some exceptions can be identified, such as redirected walking methods in which the control law is the main design component. In contrast, for virtual steering methods, only the analysis of angular speed with head rotation gains has been formally studied [SMSR17] but not the linear speed control. Since spatial steering techniques are commonly used methods due to their simplicity, it is essential to thoroughly study the potential impact of linear speed control on users' behaviour. For example, considering that the linear speed has a direct impact on the actual users' motion, it can potentially have an influence on the quality of the navigation as well as users' experience while being immersed in the VE.

The contributions of this paper are two fold. First, we propose a formal characterization of control laws for virtual steering techniques. This characterization aims at encouraging reproducibility in future experiments and provides clear guidelines for VR practitioners. Second, we designed a user study assessing how the linear speed update on virtual steering techniques can impact the users' behaviour in a navigation task. In particular, three linear speed con-

† e-mail: firstname.lastname@inria.fr

trol laws (discrete, continuous, adaptive) were evaluated in a virtual slalom navigation task considering different curvature conditions (low, medium and high curvature turns). The users' behaviour was assessed through an analysis of the spatial-temporal characteristics of their trajectories and their level of comfort was evaluated through subjective questionnaires. We found that the control law had an impact on the way users performed the navigation task. We noticed differences in users linear and angular speed profiles, and also differences in perceived physical demand and effort between the control laws. Taken together, our results contribute to the understanding of human behavior in VEs and argue that evaluating and comparing different control laws is necessary to improve their design.

2. Related Work

Virtual navigation techniques, and more precisely virtual steering techniques, can be decomposed into three main components: direction, input and speed [LKMP17]. The virtual **direction** is typically defined by one of a body segment (e.g. the head [LKMP17], the hand [CMRCL09, BWCL01] or the torso [BKH98]), or the orientation of the gaze [SD12, QT18, SG06]. It can also be defined by physical interfaces, such as leaning platforms [BBH07, MPL11, WL11] or joysticks [LLS18]. The choice of direction control is normally dependent on task constraints and hardware availability. For example, gaze-steering techniques do not require additional hardware as the user's head is typically tracked, preventing users to decouple the looking direction with the navigation direction. Hand-steering decouples the view and the navigation direction but can increase the complexity of the task. Although torso steering has not been extensively evaluated and requires to track the user's torso, it can generate user behaviours that better match the ones observed in real locomotion compared to head or hand steering techniques during curvilinear trajectories [BPK*19]. Finally, leaning-based techniques require additional hardware but leverage user proprioception (e.g. leaning) which can provide more intuitive interfaces [MPL11]. The **input** mechanism refers to the conditions of input required by the application to determine the navigation state (initiate, continue and stop) [BKH97]. Typically, navigation techniques may require continuous (e.g. a joystick) or binary inputs (e.g. a button). For instance, the motion may be automatic, therefore no input may be required. Finally, the **speed** component, which is the main scope of this paper, is described hereafter.

The control law models how the user translation and rotation viewpoint are updated in the VE considering the state of the system. It takes as input the state of the system, which encompasses the current navigation state and the user's input, but it can also consider other parameters such as the curvature of the current trajectory [BPK*19], the scale of the environment [MMGK09], the viewpoint quality [FWK16] or the user's perceived motion [Arg14]. The control law, in addition to provide a smooth control of the navigation speed, must handle two particular states, namely the beginning and the end of the motion [BKH98]. Rotational speed update laws are less used since it has been proven that altering users rotational speed with a joystick can provoke cybersickness [LLS18]. In the context of virtual steering, other works have explored the impact of rotational gains for virtual steering techniques [SMSR17] on spatial orientation and navigation performance. In this paper, we will only focus on the linear speed update for virtual steering techniques. To enable speed changes, control laws determine the navigation speed given the user's inputs (discrete, e.g. a button press or continuous, e.g. a joystick) and a transfer function that defines the mapping between each input data and transforms it into an output value [FHKH06]. According to their degree of control, control laws can be categorized in three different groups: discrete, continuous and adaptive.

Discrete control laws enable the user to select one navigation speed from a predefined set of speeds. The simplest law will consider just one speed, i.e. the user presses a button to navigate and releases it to stop. Other implementations might consider a wider range of speeds (e.g. one button to increase the speed, an another to decrease it). The designer of the application has to determine the actual navigation speed values. The optimal navigation speed for human scale environment would range between 1m/s and 1.4m/s, as demonstrated both in Real Environment (RE) [Boh97] and VE [FFW07]. **Continuous** control laws increase the users control over the final navigation speed by allowing them to choose the speed over a continuous scale. A basic implementation is to linearly map the input range of a joystick axis to the range between the minimal and the maximal navigation speeds. Continuous control laws are typically used on lean-based techniques, for example specifying the speed according to the position of the head relative to the body [SN93]. Depending on the application, quadratic or logarithmic mappings could also be considered. Finally, **adaptive** control laws take into account additional system states in order to adjust the navigation speed. A number of adaptive techniques has explored the relative position of the user with respect to the virtual environment. Freitag et al. [FWK16] proposed to adjust the navigation speed in function of the amount of information visible from the user's viewpoint. Boustila et al. [BCB15] considered the VE to decrease the navigation speed according to the number of virtual objects and their distance from the user. Another example is the work from Argelaguet et al. [Arg14] in which the spatial relationship between the user and the virtual environment on one side and the perceived navigation speed on the other side is used to adjust the speed. In contrast, other techniques have explored the trajectory of the user to modulate the navigation speed. The Joyman [MPL11] modulates the tangential speed according to the actual rotational speed, in order to better resemble the dynamics of real walking. Brument et al. introduced a control law inspired of the biomechanics of human walking that uses the relationship between speed and curvature during a continuous trajectory [BPK*19]. Finally it is also possible to use physiological measures such as electrodermal activity to adjust the navigation speed [PCM18].

In overall, discrete control laws are easy to use, but might generate navigation speeds that are not always well adapted to all navigation tasks. Continuous laws, although they increase the user control, are more complex to operate. Finally, adaptive laws try to provide the optimal navigation state but can also generate a lack of perceived control and thus potentially increase user frustration. Although a number of works have assessed virtual steering techniques in terms of performance [NSBK15], or spatial awareness [LLS18], the role that the linear speed has on the user's behaviour remains largely unexplored. Thus, the main goal of this paper is to assess whether linear speed on virtual steering techniques can have an impact on the users' behaviour, in particular on the performed trajectories. Before detailing the user study, we also propose a characterization of control laws for steering techniques to define and compare the several existing control laws in the literature.

3. Characterization of Control Laws

The control law defines how the navigation states (e.g. linear and rotational speed) are updated at each time step considering users and system inputs. Most of the existing classifications and taxonomies tend to overlook the details of the control law and mainly focus on navigation metaphors and input mechanisms, except for few examples [BKH98, AHKV04, NB16]. Thus, researchers and practitioners are faced with the need to design the control law and manually adjust its parameters (e.g. maximum speed, acceleration/deceleration rate) for each experiment or application. The goal of this section is to characterize navigation control laws to encourage reproductibility in future experiments and provide clear guidelines for VR practitioners. Furthermore, we present three full examples corresponding to the control laws that we evaluated in our user study (see Section 4).

3.1. Main Components

When characterizing a control law, two major components should be defined: the input data and the transfer function. The input data comprise the user's input and the system state. The transfer function determines a new navigation state, using the input data. The navigation state encloses all the elements that are involved in the computation of the next virtual camera position and orientation: tangential speed/acceleration, rotational speed/acceleration, camera position and orientation. The navigation state can be also an input for the transfer function.

3.1.1. Input Data

User's input data is provided by input devices (e.g. tracking data, buttons or joysticks). The input data determines the actions that the user has to perform to operate the navigation technique and its degree of control. For further information about the wide variety of existing input devices for virtual steering techniques, please refer to [LKMP17]. **State input data** is extracted by the current and/or the past state of the system. State input data can range from the curvature of the current trajectory [BPK*19], the scale of the environment [MMGK09], the viewpoint quality [FWK16] or the user's perceived motion [Arg14]. State input data is commonly used in adaptive techniques.

3.1.2. Transfer Function

A transfer function defines the mapping between the input data and the next navigation state [FHKH06]. When navigating in VEs, the transfer function is responsible for updating the kinematics of the virtual camera, therefore updating the following navigation states:

- **Heading -** The current direction of the motion. For steering techniques, the navigation direction is generally determined by a user's body segment such as the head, the hand or the torso, and defined by pointing or looking to the desired direction, although it can also be updated according to the rotation speed and acceleration.
- **Linear speed -** The velocity of the virtual camera which is tangential to the heading direction. In most implementations, the tangential speed is set to a constant value or it is computed with a linear function that takes into account user's input.
- **Linear Acceleration -** The acceleration of the virtual camera. Generally, the acceleration is computed as the time derivative of the tangential speed.
- **Position -** The position of the virtual camera. The camera position is normally updated using either a constant translation or defined by the linear speed and acceleration.
- **Rotation speed -** The rotation speed of the virtual camera. Although the virtual camera orientation, in a HMD context, is in most cases equal to the user's head orientation, redirected techniques or joystick-based navigation require transfer functions to update camera's orientation.
- **Rotation acceleration -** The rotation acceleration of the virtual camera. As the linear acceleration, it can be a derivative of the rotation speed or manually defined.

The following section illustrates the design of control laws based on the linear speed transfer function.

3.2. Control Law Design Example

The design constraints are that the user should be able to control the linear speed using a 1DoF input device and the heading is defined with an isometric mapping with respect to the user's torso orientation (i.e. torso steering). A generic transfer function is presented in Algorithm 1. This function computes at every frame the current speed (S_t) and acceleration (A_t) taking into account the user input (in our experiment, the trigger's pressure from the HTC Vive controller, $trig \in [0;1]$; where 0 means the trigger is released and 1 entirely pressed) and the simulation time (Δt). When the user is providing input (Lines 2 to 8), the algorithm computes a target speed (S_t) and limits the generated acceleration (Line 4 and 8) to avoid potentially high accelerations. If the user is not providing input (Lines 10 to 14) the acceleration is set to stop the motion. For practical reasons, we only considered forward motions in our user study. Finally, the computed acceleration is used to define the final speed (S_t) and the specific case handling the motion end. Three constants are required: the maximum and minimum linear speed ($S_{max} = 1.4 m/s$, $S_{min} \approx 0$) and the maximum and minimal linear acceleration ($A_{max} = 1 m/s^2$, $A_{min} = -1 m/s^2$). The maximum navigation speed and acceleration are set to match a comfortable walking speed in a real environment. Regarding the main behaviour of the transfer function (Line 2), we focused on three alternatives with different degrees of control: constant, linear and adaptive.

The **constant** transfer function has a binary behaviour, either the user is not moving (i.e. not pressing the controller's trigger) or he is navigating at S_{max} (i.e. pressing the controller's trigger). Therefore the function always outputs S_{max}:

$$S_t \leftarrow S_{max} \tag{1}$$

The **linear** transfer function takes into account the continuous nature of the input data and sets the speed according to the controller's trigger pressure ($trig$):

$$S_t \leftarrow trig * S_{max} \tag{2}$$

Algorithm 1 General Speed Transfer Function

if $trig != 0$ **then**
    $S_t \leftarrow$ SpeedTransferFunction(S_{max}, $trig$)
    $A_t \leftarrow (S_t - S_{t-1}) / \Delta t$
    if $A_t > 0$ **then**
        $A_t \leftarrow$ Min(A_t,A_{max});
    else
        $A_t \leftarrow$ Max(A_t,A_{min});
    end if
else
    if $S_{t-1} > S_{min}$ **then**
        $A_t \leftarrow -A_{max}$
    else
        $A_t \leftarrow 0$
    end if
end if
$S_t \leftarrow S_{t-1} + A_t \Delta t$
if $S_t < S_{min}$ **then**
    $S_t \leftarrow 0$
    $A_t \leftarrow - S_{t-1} / \Delta t$
end if

Finally, for the **adaptive** transfer function, we chose a function that takes into account the relationship between the speed and the curvature of the actual trajectory in human walking [BPK*19]. During a continuous trajectory, the instantaneous speed varies according to the local radius of the curvature (see Equation 3) as a power law (Equation 4):

$$R_t = \frac{(\dot{x}^2 + \dot{z}^2)^{\frac{3}{2}}}{\dot{x}.\ddot{z} - \ddot{x}.\dot{z}} \tag{3}$$

where $\dot{x}$, $\dot{z}$, $\ddot{x}$ and $\ddot{z}$ are respectively the first and second derivatives of x and z coordinates of the user's position in the environment. This function derives from the control of human walking trajectory in a curve, where the speed of locomotion is, in the case of walking trajectories, proportional to the cubic root of the radius of curvature [VKDB01, HVR*05]:

$$S_t = K.R_t^{\frac{1}{3}} \tag{4}$$

where S_t is the horizontal speed at time t, K is a gain speed coefficient and R_t is the radius of local curvature of the trajectory at time t. We set the coefficient $K = 0.6$. Therefore, we computed the virtual speed according to user's position in the VE using Equation 4.

Such characterization allows practitioners to design every elements that a control law must provide. In the next section, we assess the potential impact of different control laws on the user's behaviour.

4. User Study

The goal of this experiment was to investigate the effects of control laws on users' behavior and preferences during a navigation task with curved trajectories. We wanted to study in particular the way users perform different type of turns (by varying the trajectory's curvature) with virtual steering techniques. To this end, we designed a slalom task as it involves a continuous navigation with several turns, therefore inducing speed and orientation adaptations. The considered task, although it does not represent an ecologic task in a VE, allows to assess the control laws in a controlled and standardized manner.

4.1. Participants and Apparatus

18 participants (16 males and 2 females) aged between 22 and 31 years old (25.11±2.39, mean±SD) without any ocular or locomotion disorders volunteered to this study. 14 participants reported using VR on a weekly or daily basis, 3 few times and 1 never. All participants except one had regular experiences with videos games. They were naive to the purpose of the experiment and signed an informed consent form. The study was conformed with the standards of the declaration of Helsinki. We use a Vive HMD to immerse the users in the VE and 2 HTC Vive trackers, fixed to a backpack carried by the participants, to track users' shoulders. The reference coordinate system was defined by the HTC Vive tracking system. During the whole experiment we guaranteed the maximum framerate of the HMD. The cables of the HMD were hanging from the ceiling to prevent users from being bothered by them.The VE was a large plane with a noisy texture in order to generate motion flow from participants' rotations but without any salient features. The virtual slalom consisted in 12 turns defined as a sinusoidal-like trajectory (Figure 1). We set up three slaloms with the same amplitude ($a = 2m$) but with different frequencies f to modify the trajectory's curvature and alter the task difficulty: Small Curvature (SC), $f = 1$; Medium Curvature (MC), $f = 1.5$ and High Curvature (HC), $f = 2$. To indicate the path to follow without constraining too much the trajectory, participants had to go through virtual gates (1x2.3x1 meters) located at the peaks of the sinusoidal trajectory (Figure 1). The beginning of the trajectory was indicated by a black cross displayed on the ground. Only the ground and the gates were displayed during the task.

4.2. Design and Hypotheses

We used a repeated-measures design in which the independent variables were the **control law**: constant (C), linear (L) or adaptive (A) and the **curvature type**: small (SC) medium (MC) and high

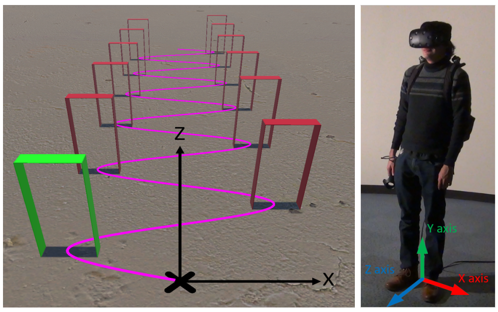

Figure 1: *Left - The VE used for the experiment. Users started from the black cross and performed a 12 gates slalom. The order of the gates is shown by the pink path, only represented here for explanatory purposes. The green gate represented the next gate to cross. Right - Participant equipped with the HTC Vive HMD, a backpack, the HTC Vive trackers and controller.*

(HC). Our hypotheses were: **[H1]** The control law and the curvature would influence the performance (e.g. time, distance) and the spatio-temporal parameters (e.g. speed, acceleration and angular profiles) of the trajectories. **[H2]** Users would report better comfort and subjective results with the adaptive control law. With these hypotheses, we suggest that the control law, but also the type of trajectory, could influence users' navigation. In particular, we expect that the adaptive control law would be better suited for the task, especially for high curvature turns, since its design is based on the biomechanics of natural walking.

4.3. Procedure

First, participants read and signed the consent form which provided detailed information regarding the experiment. The experiment consisted in three randomized blocks, one for each control law. Each block considered 1 training trial to get familiar with the task and 12 randomized experimental trials (4 trials per curvature type). Each trial involved participants to perform 6 left and 6 right turns. The experiment therefore resulted in a total of 39 trials (3 control laws x 13 trials), namely 468 turns (39 trials x 12 turns) per participants. Before the beginning of each block, participants filled a Simulator Sickness Questionnaire (SSQ) [KLBL93]. Each experimental trial followed the procedure described hereafter. Participants were facing at the gates and started their trajectory at the black cross in the VE (Figure 1). Once placed on the black cross, they could trigger a 3 seconds countdown by pressing the touchpad before starting the trial. Then, they performed the slalom using the control law defined for the current block. At the end of the trial, we asked them to answer the question "How comfortable the trial was?" on a 7-point Likert scale, where 1 was "not comfortable at all" and 7 "very comfortable". After each block, the users took off the VR equipment, then filled a SSQ questionnaire, a NASA Task Load Index (NASA-TLX) form [Har86] and the USE questionnaire [Lun01] (considering only the *Ease of Learning* dimension. Between blocks, participants had a 5 minutes break. The order of the conditions was counterbalanced using a latin-square design. In total, the experiment took approximately one hour.

4.4. Data Analysis

We removed the first and last turns from each trial since we wanted to analyze the behavior during the continuous trajectory, therefore not considering the beginning and the end of the trajectory. We conducted two main analyses, one focusing on the trajectory performed during the entire trial (global) and a second considering only the slalom turns (local). We defined a turn as the trajectory between two inflexion points of the sinusoidal-like trajectory. We resampled positions and orientations of head and shoulders, and then applied a butterworth low-pass filter with a cutoff frequency of 1 Hz and finally temporally normalized them in order to evaluate the effect of our experimental conditions over time. We gathered the time required to perform the task and computed distances achieved in both VE and RE. We computed participants' trajectories in the VE as well as their physical movements in the RE (i.e. their torso rotation and translation) as the shoulders' barycenter trajectories (CG). During the pilot studies we observed that some participants had the tendency to drift over time (unintentional positional drift). Although they do not have to physically walk, they might end up to few meters away from the starting point. Thus, we considered that their motion in the RE could be valuable. We then computed participants' linear speed and acceleration as respectively the first and second time derivatives of the CG. To evaluate the effect of our independent variables on average kinematics of the trajectories, we performed a two-way analysis of variance (ANOVA) with repeated measures when the distribution of the dependent variables was normal or an Aligned Rank Transformation (ART) ANOVA test if not [WFGH11]. Normality was assessed using the Shapiro-Wilk test. Greenhouse-Geisser adjustments to the degrees of freedom were applied, when appropriate, to avoid any violation of the sphericity assumption. Post-hoc analysis was based on pairwise t-tests with Bonferonni corrections. To evaluate the effect of the experimental factors over time (time normalized over 1 turn), we used the Statistical Parametric Mapping (SPM) method [FAK*07]. This analysis allows comparing time-series data of different trials taking into account their variability at each time-step. Finally, to analyse subjective data from the questionnaires, we used the Friedman test and post-hoc pairwise Wilcoxon tests with Bonferroni corrections.

4.5. Results

4.5.1. Trajectories, Time and Distance

Figure 2 shows the average virtual path followed by participants depending on the control law and the curvature type. It illustrates the great similarity regarding the path followed for a given curvature across the 3 control laws. In addition, Table 1 reports average spatio-temporal characteristics of the trajectories. ART ANOVAs showed that the control law ($F_{2,34} = 62.22$, $p < 0.001$), as well as the curvature type ($F_{2,34} = 44.76$, $p < 0.001$) had an effect on trial duration, being longer with the adaptive control law ($p < 0.05$), and when performing the SC condition ($p < 0.05$).

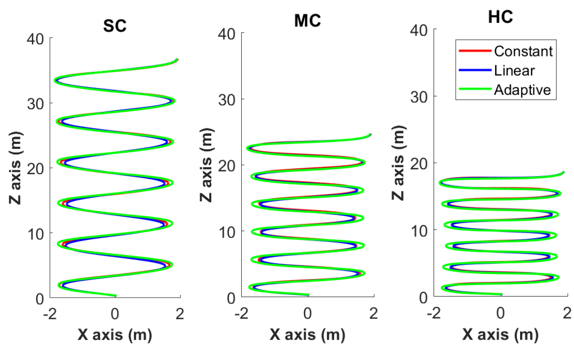

Figure 2: *Average path (after filtering the data) followed by participants depending on control law and curvature type.*

We found an effect of the curvature type on the distance achieved in the RE (i.e. displacement of the CG) ($F_{2,34} = 3.49$, $p < 0.05$), where the bigger the curvature was, the higher the users movement achieved in the RE were ($p < 0.05$). Besides, we noticed that the displacement from the starting position in both X and Z axes were higher when performing the HC condition than the others ($F_{2,34} = 3.50$, $p < 0.05$ for X axis, $F_{2,34} = 54.15$, $p < 0.001$ for Z axis).

Table 1: *Mean and standard deviation, reported as M (SD), for time execution, distance achieved in VE and RE for each control law and curvature type for the whole trial. The two effect columns report respectively whether there was a significant effect of the control law or of the curvature type on the studied variables (* for $p < 0.05$, ** for $p < 0.01$, *** for $p < 0.001$). Post-hoc tests (with Bonferonni corrections) for main effects are reported using superscripts. Two levels sharing the same superscript are not significantly different.*

	Constant	Linear	Adaptive	Effect	SC	MC	HC	Effect
Time execution (sec)	40.74 (3.93)^1	41.262 (5.26)^1	48.80 (4.56)^2	***	42.49 (6.41)^1	42.66 (5.96)^1	45.65 (4.73)^2	***
Distance VE (m)	55.93 (4.48)	55.50 (4.66)	55.83 (5.70)		60.01 (3.43)^1	54.31 (3.99)^2	52.94 (4.48)^3	***
Distance RE (m)	6.39 (2.18)	6.72 (2.31)	6.62 (2.55)		5.98 (2.40)^1	6.65 (2.21)^2	7.09 (2.32)^3	***
Linear speed (m.s^{-1})	1.37 (0.07)^1	1.36 (0.10)^1	1.14 (0.05)^2	***	1.32 (0.11)^1	1.29 (0.13)^2	1.26 (0.07)^2	***
Acceleration (m.s^{-2})	0.033 (0.004)^1	0.032 (0.005)^1	0.019 (0.002)^2	***	0.028 (0.006)^1	0.029 (0.008)^2	0.029 (0.009)^2	***
Angular speed (rad.s)	0.83 (0.14)^1	0.82 (0.15)^1	0.678 (0.10)^2	***	0.625 (0.06)^1	0.81 (0.09)^2	0.90 (0.12)^3	***

4.5.2. Linear Speed, Acceleration and Angular Speed

Figure 3 shows the average and standard deviation of the temporal evolution of the linear speed, acceleration and angular speed depending on the curvature type and the control law. SPM analysis showed an effect of the control law on these time-series during the turn. Post-hoc tests demonstrated that the linear speed, acceleration and angular speed were smaller for the adaptive control law than the constant or linear ones ($p < 0.05$) during the turn. However, no difference was observed between constant and linear that had similar profiles.

Mean linear speed — An interaction effect was found ($F_{4,68} = 14.20$, $p < 0.001$) in which the control law had an effect on the mean linear speed for the entire trial ($F_{2,34} = 75.90$, $p < 0.001$) as well as the curvature type ($F_{2,34} = 41.40$, $p < 0.001$). Post-hoc comparisons showed that participants linear speed was slower with the adaptive control law than the constant or linear ones ($p < 0.05$) and faster during the SC than the MC or HC ($p < 0.05$). However, during the turns, we reported only an effect of the control law ($F_{2,34} = 63.13$, $p < 0.001$) where participants' linear speed was slower with the adaptive control law than the others ($p < 0.05$).

Mean acceleration — We noticed an effect on the control law ($F_{2,34} = 95.152$, $p < 0.001$), the curvature type ($F_{2,34} = 8.733$, $p < 0.001$) and an interaction effect ($F_{4,68} = 10.65$; $p < 0.001$). Post-hoc analysis determined on one hand that, the adaptive control law provided slower acceleration than the constant or the linear control laws ($p < 0.05$) and on the other hand that the higher the curvature type was, the higher the mean acceleration was ($p < 0.05$).

Mean angular speed — We observed an effect of the control law ($F_{2,34} = 89.416$, $p < 0.001$), the curvature type ($F_{2,34} = 238.88$, $p < 0.001$) and an interaction effect ($F_{4,68} = 15.62$, $p < 0.001$). Post-hoc tests showed that the lower the curvature type is, the lower is the mean angular speed and the adaptive control law produced lower angular speed profiles than the constant or linear control laws.

4.5.3. Subjective Questionnaires

None of the participants experienced simulator sickness symptoms and we did not report any effect of the control law on the average SSQ scores. We also noticed no effect on the average values of the USE (*Ease of Learning dimension*) questionnaire. TLX-NASA questionnaire scores presented an effect on the physical demand subscale ($\chi^2(2) = 6.65$, $p < 0.05$), but post-hoc comparison showed no effect between the different control laws (Figure 4). Besides, the effort subscale showed an effect on the control law ($\chi^2(2) = 7.84$, $p < 0.05$) but post-hoc comparison did not show effect between the different control laws (Figure 4). Regarding the question asked at the end of each trial, we found an effect on the curvature type ($F_{2,34} = 16.37$, $p < 0.001$), where the SC appeared the most comfortable curvature type and the HC the least comfortable ($p < 0.05$).

5. Discussion

Our objective was to assess whether the control laws could influence how users perform navigation in VEs. We designed an experiment where participants had to perform a virtual slaloms with different curvature types using 3 different control laws. Our results showed an effect of the control law, that generated different users' movements for a given slalom, but also an effect of the curvature type where the curvature influenced the way users performed the slalom task.

5.1. Influence of Curvature on Users Movements and Trajectories

Considering the movements in the RE, we showed that the higher the curvature, the higher the user's displacements in the RE. These movements results in unintentional positional drift, where the users were drifting from their initial position in the RE while navigating in the VE. Some participants had high unintentional positional drift in the RE, almost reaching the limits of the physical workspace. Yet, we did not observe an effect of the control law. Then, we suggest that the drift could be more dependent on the amount of physical rotation required, and in particular to perform high curvature trajectories. This result has a strong relevance for VR setups with a limited workspace size as it suggests that, even for steering techniques, users might reach the physical boundaries of the workspace after a short navigation period. This could have an effect on the users safety and may break their presence in the VE. While methods to avoid such situations has been largely explored for full gait techniques, such as redirected walking [RKW01] or resetting techniques [WNR*07], it remains unexplored for virtual steering techniques. An additional observation concerns the possibility to manually modulate the navigation speed with the linear control law, where users can increase or decrease their speed using trigger controller. Yet, our results showed

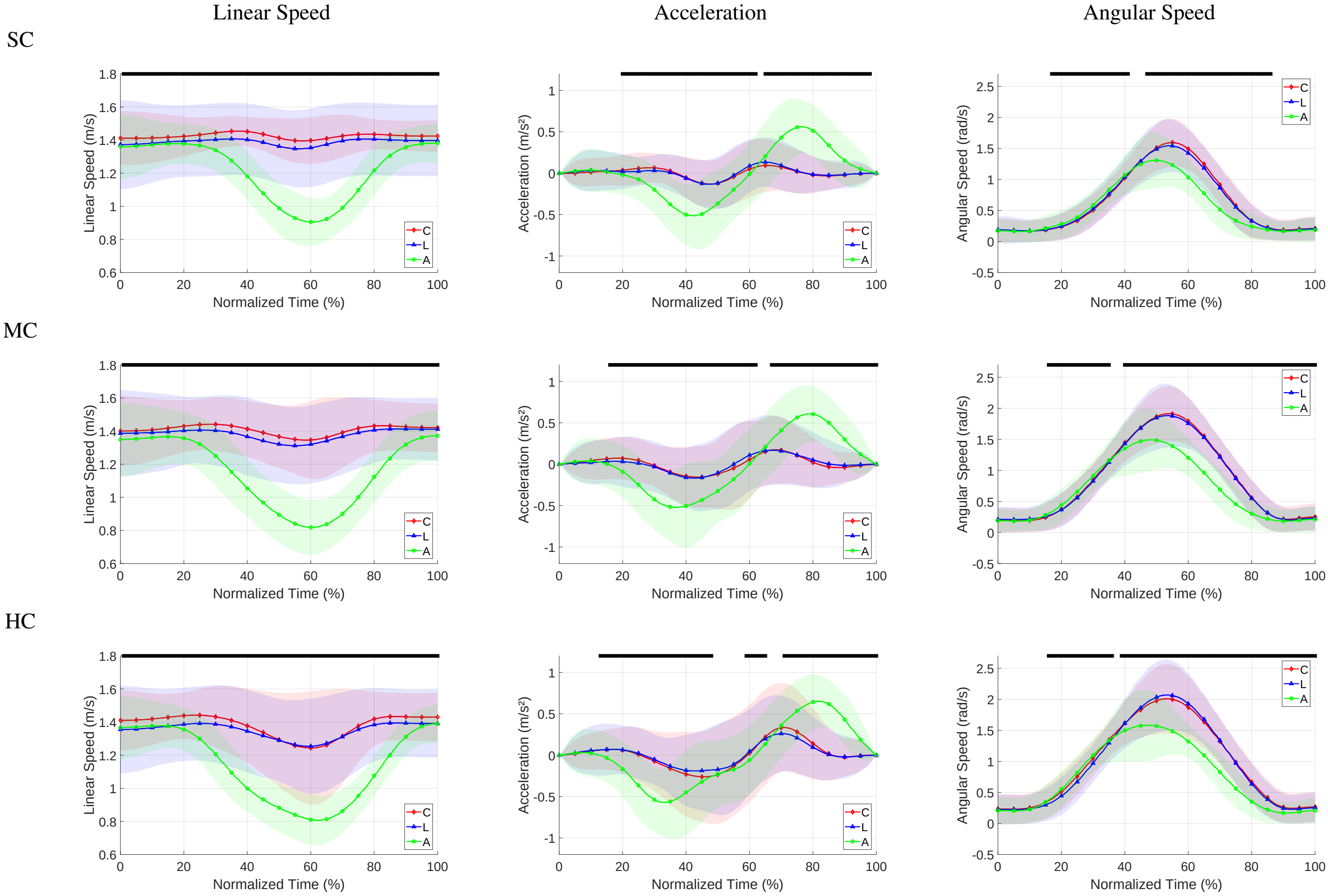

Figure 3: *This figure shows averaged temporal evolution of mean and standard deviation of linear speed, acceleration and angular speed for each control law (constant (C) in red, linear (L) in blue and adaptive (A) in green) and curvature type (SC on first row, MC on second and HC on third) during turns for all participants. Each sample of the temporal sequence is a dependant variable. The part where the control law has an effect is represented by the black line meaning that the F value for this variable is higher than the F^* computed. We can notice that there is an effect of the control law on the variables during most of the turn duration. Besides, the linear speed, acceleration and angular speed profiles differ according to the curvature type.*

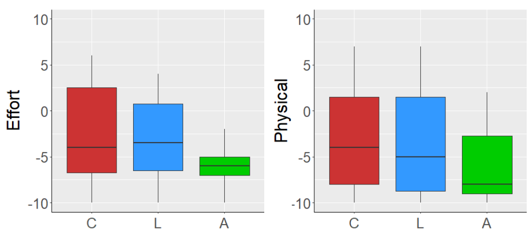

Figure 4: *Boxplots of the TLX results per control laws (C for constant, L for Linear and A for Adaptive) for Effort and Physical Demand subscales. -10 indicates a very low effort or physical demand whereas 10 indicates a very high effort or physical demand.*

that they did not use this possibility. We did not find difference between linear and constant speed profiles as shown in Figure 3, meaning that they were always pressing the trigger to its maximum in order to reach the maximum navigation speed ($1.4 m/s$). We could have set a higher maximum speed for the linear law, allowing participants to continuously modulate the current virtual speed instead of clamping it, but it would have introduced a bias in our experimental design since the three control laws would not have had the same maximum values. Future work can further investigate if users take advantage of linear control laws, in which they can dynamically update their tangential speed, during complex navigation maneuvers.

5.2. Control Laws Can Alter Kinematics

Regarding comparison of the control laws, Figure 3 summarizes typical temporal evolution of linear and angular speed for each control laws. We can notice different variability in the **linear speed** profiles according to the curvature type for the constant and linear conditions (HC generates more variability for these control laws than the MC or SC ones), where this variability is lower for the adaptive one (more similar profiles regardless of the curvature type). Research on biomechanics of walking in REs showed a relation between the trajectory curvature and the walking speed [VKDB01]. Since the adaptive control law is based on this relation, we suggest that participants better adapted their behavior with this one than the others. One reason is that this law generated similar linear speed profiles than walking in REs, allowing users to keep a consistent behavior across the different curvature types. We also noticed a significant difference for each curvature type between the **acceleration** profiles produced by the adaptive control law, and both constant and linear laws. This can be explained by the fact that most of the participants were navigating at the maximum speed during turns, resulting in acceleration profiles close to $0 m/s^2$). In contrast, the adaptive law generated deceleration profiles before the turns and acceleration profiles after them. Besides, acceleration profiles variability can be explained by the users physical motion. For example, we can notice in Figure 3 that higher curvatures generated higher variability in the acceleration profiles, where it remained consistent for the adaptive one. Finally, the **angular speed** profiles were also altered by the control law and the curvature type. Figure 3 shows that participants rotated faster their torso with the constant and linear control laws than the adaptive one. For the adaptive law, as the speed was adjusted according to the curvature of the user's trajectory, it enforced lower speeds. This adaptation generated a change on turning behaviour, inducing lower angular speeds. However for the constant or linear ones, where the linear speed profiles were higher, participants preferred to compensate the higher speed by rotating faster their torso in order to turn faster (involving higher angular speed profiles) than releasing the controller trigger to decrease the virtual speed and cross the gates with a lower angular speed. We argue that having control laws that provide lower angular speed could improve users' navigation because fast body rotations may degrade users trajectories and could increase cybersickness [FT18]. In overall, these results confirmed our first hypothesis **[H1]**, for a given task, the control law and the curvature type can influence the spatio-temporal parameters (displacements in RE, linear speed, angular speed and acceleration profiles) of the trajectory.

5.3. Towards Control Laws Based on Human Behavior?

The TLX-NASA analysis revealed a main effect of the control law on the physical demand and effort subscales. Although post-hoc comparisons could not confirm it, a visual inspection of the results (see Figure 4) suggests that participants had a lower perception of physical and effort demand for the adaptive law. This can be explained by the lower angular speed profiles generated with the adaptive control law that decreases the turning effort to perform slaloms. Therefore, the different TLX scores between the adaptive control law and the constant or linear ones can have two interpretations: (1) the lower angular speed profiles provided somehow more comfort resulting in lower effort to perform the task, or (2) the perception of the trajectory motion generated by the adaptive law seemed similar to an equivalent trajectory performed by real walking. These hypothesis might be explained by a higher locomotion fidelity for the adaptive control law than the others. Yet, further research is required to validate these suggestions. An interesting point about users' behavior, is that we noticed that had different strategies while navigating, resulting in different physical body rotations and translations. However, this behavior was consistent for each user across the three control laws. We informally reported four typical behaviors: (1) No translations in the RE with full-body rotation (including feet) during the turns. (2) No translations in the RE but only upper-body rotations (only the torso was rotating). (3) Translations in the RE with full-body rotations. (4) Translations in the RE with upper-body rotations. We suggest that participants shifted in the RE either with forward translations to navigate faster (i.e. to follow the forward virtual translation in the VE) if they felt comfortable to perform the navigation task ; or backwards to counterbalance the high curvature turns (i.e. stepping back in the RE to be able to cross the gate without collisions in the VE) if they felt uncomfortable to perform the navigation task. Regarding the orientation, we noticed that high curvature implied full-body rotations and it was difficult for participants to only rely on upper-body rotations. Nevertheless, more investigation is required in order to better understand in which situations users tend to use one of these patterns and if every participant had the same behavior according to the control law and curvature type. These results, although they do not fully support **[H2]**, provide insights on how the control law can alter users' experience while navigating. Taken together, our experiment showed that a navigation involving turns and body rotations could alter user behavior. Developers should then consider control laws with respect to the type of trajectories users should have in the VR application. While constant and linear laws are popular in VR applications and can be still creditable for straight trajectories, our results would recommend the use of adaptive control laws when trajectories involve high curvature turns, as they could improve users' comfort.

6. Conclusion and Future Work

In this paper, we first proposed a characterization of control laws for spatial steering navigation in VEs and second, we described an evaluation of three different control laws in a virtual slalom task. While the characterization aims at encouraging reproducibility in future experiments and providing guidelines for VR practitioners on the design of control laws, the experiment explored the impact that the control law might have on user's performance and behaviour. Our results showed that the control law and the type of trajectory altered the spatio-temporal parameters of the trajectories, in particular the angular speed profiles. The adaptive control law showed encouraging results that arouse interest about the potential use of control laws based on human locomotion for trajectories that requires high curvature turns. However, future studies should consider VEs that better represent ecological situations, as well as evaluations of the control law at the individual level. These works could improve the existing control laws by being more adapted to the user and the task. To sum up, these results highlight the relevance that the control law can have on virtual steering and that human motor control knowledge is a promising research avenue to improve its design.

References

[AHKV04] ANTHES C., HEINZLREITER P., KURKA G., VOLKERT J.: Navigation models for a flexible, multi-mode vr navigation framework. In *Proc. of VRCAI* (2004), vol. 4, pp. 476–479. 3

[Arg14] ARGELAGUET F.: Adaptive navigation for virtual environments. In *Proc. of IEEE Symposium on 3D User Interfaces* (2014), pp. 123–126. 2, 3

[BBH07] BECKHAUS S., BLOM K. J., HARINGER M.: Chairio–the chair-based interface. *Concepts and technologies for pervasive games: a reader for pervasive gaming research 1* (2007), 231–264. 2

[BCB15] BOUSTILA S., CAPOBIANCO A., BECHMANN D.: Evaluation of factors affecting distance perception in architectural project review in immersive virtual environments. In *Proc. of ACM Symposium on Virtual Reality Software and Technology* (2015), pp. 207–216. 2

[BH99] BOWMAN D. A., HODGES L. F.: Formalizing the design, evaluation, and application of interaction techniques for immersive virtual environments. *Journal of Visual Languages & Computing 10*, 1 (1999), 37 – 53. 1

[BJH01] BOWMAN D. A., JOHNSON D. B., HODGES L. F.: Testbed evaluation of virtual environment interaction techniques. *Presence: Teleoperators and Virtual Environments 10*, 1 (2001), 75–95. 1

[BKH97] BOWMAN D. A., KOLLER D., HODGES L. F.: Travel in immersive virtual environments: an evaluation of viewpoint motion control techniques. In *Proc. of IEEE Annual International Symposium on Virtual Reality* (1997), pp. 45–52, 215. 2

[BKH98] BOWMAN D. A., KOLLER D., HODGES L. F.: A methodology for the evaluation of travel techniques for immersive virtual environments. *Virtual Reality 3*, 2 (June 1998), 120–131. 1, 2, 3

[Boh97] BOHANNON R. W.: Comfortable and maximum walking speed of adults aged 20-79 years: reference values and determinants. *Age and Ageing 26*, 1 (1997), 15–19. 2

[BPK*19] BRUMENT H., PODKOSOVA L., KAUFMANN H., OLIVIER A. H., ARGELAGUET F.: Virtual vs. physical navigation in vr: Study of gaze and body segments temporal reorientation behaviour. In *Proc. of IEEE Conference on Virtual Reality and 3D User Interfaces* (2019), pp. 680–689. 2, 3, 4

[BWCL01] BOWMAN D., WINGRAVE C., CAMPBELL J., LY V.: *Using pinch gloves (tm) for both natural and abstract interaction techniques in virtual environments*. Tech. rep., Virginia Tech, 2001. 2

[CMRCL09] CIRIO G., MARCHAL M., REGIA-CORTE T., LÉCUYER A.: The magic barrier tape: A novel metaphor for infinite navigation in virtual worlds with a restricted walking workspace. In *Proc. of the ACM Symposium on Virtual Reality Software and Technology* (2009), pp. 155–162. 2

[FAK*07] FRISTON K., ASHBURNER J., KIEBEL S., NICHOLS T., PENNY W.: *Statistical Parametric Mapping*. Academic Press, 2007. 5

[FFW07] FINK P. W., FOO P. S., WARREN W. H.: Obstacle avoidance during walking in real and virtual environments. *ACM Trans. Appl. Percept. 4*, 1 (2007). 2

[FHKH06] FROHLICH B., HOCHSTRATE J., KULIK A., HUCKAUF A.: On 3d input devices. *IEEE computer graphics and applications 26*, 2 (2006), 15–19. 2, 3

[FT18] FARMANI Y. Y., TEATHER R. J.: Viewpoint snapping to reduce cybersickness in virtual reality. In *Proc. - Graphics Interface* (Jan. 2018), pp. 159–166. 8

[FWK16] FREITAG S., WEYERS B., KUHLEN T. W.: Automatic speed adjustment for travel through immersive virtual environments based on viewpoint quality. In *Proc. of IEEE Symposium on 3D User Interfaces* (2016), pp. 67–70. 2, 3

[Har86] HART S. G.: *NASA Task Load Index (TLX). Volume 1.0; Computerized Version*. Tech. rep., NASA, 1986. 5

[HVR*05] HICHEUR H., VIEILLEDENT S., RICHARDSON M., FLASH T., BERTHOZ A.: Velocity and curvature in human locomotion along complex curved paths: a comparison with hand movements. *Experimental brain research 162*, 2 (2005), 145–154. 4

[KLBL93] KENNEDY R. S., LANE N. E., BERBAUM K. S., LILIENTHAL M. G.: Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The International Journal of Aviation Psychology 3*, 3 (1993), 203–220. 5

[LKMP17] LAVIOLA J. J., KRUIJFF E., MCMAHAN RYAN P. BOWMAN D. A., POUPYREV I.: *3D User Interfaces: Theory and Practice*. Addison Wesley Longman Publishing Co., Inc., 2017. 1, 2, 3

[LLS18] LANGBEHN E., LUBOS P., STEINICKE F.: Evaluation of locomotion techniques for room-scale vr: Joystick, teleportation, and redirected walking. In *Proc. of the Virtual Reality International Conference-Laval Virtual* (2018), p. 4. 2

[Lun01] LUND A. M.: Measuring usability with the use questionnaire. *Usability interface 8*, 2 (2001), 3–6. 5

[MMGK09] MCCRAE J., MORDATCH I., GLUECK M., KHAN A.: Multiscale 3d navigation. In *Proc. of the ACM symposium on Interactive 3D graphics and games* (2009), pp. 7–14. 2, 3

[MPL11] MARCHAL M., PETTRÉ J., LÉCUYER A.: Joyman: A human-scale joystick for navigating in virtual worlds. In *Proc. of IEEE Symposium on 3D User Interfaces* (2011), pp. 19–26. 2

[NB16] NABIYOUNI M., BOWMAN D. A.: A Taxonomy for Designing Walking-based Locomotion Techniques for Virtual Reality. In *Proc. of the ACM Companion on Interactive Surfaces and Spaces* (2016), pp. 115–121. 3

[NSBK15] NABIYOUNI M., SAKTHEESWARAN A., BOWMAN D. A., KARANTH A.: Comparing the performance of natural, semi-natural, and non-natural locomotion techniques in virtual reality. In *Proc. of IEEE Symposium on 3D User Interfaces* (2015), pp. 3–10. 1, 2

[PCM18] PLOUZEAU J., CHARDONNET J., MERIENNE F.: Using Cybersickness Indicators to Adapt Navigation in Virtual Reality: A Pre-Study. In *Proc. of IEEE Conference on Virtual Reality and 3D User Interfaces* (2018), pp. 661–662. 2

[QT18] QIAN Y. Y., TEATHER R. J.: Look to Go: An Empirical Evaluation of Eye-Based Travel in Virtual Reality. In *Proc. of the ACM Symposium on Spatial User Interaction* (2018), pp. 130–140. 2

[RKW01] RAZZAQUE S., KOHN Z., WHITTON M. C.: *Redirected Walking*. Tech. rep., DUniversity of North Carolina, Chapel Hill, North Carolina, USA, 2001. 6

[RVB13] RUDDLE R. A., VOLKOVA E., BÜLTHOFF H. H.: Learning to Walk in Virtual Reality. *ACM Trans. Appl. Percept. 10*, 2 (June 2013), 11:1–11:17. 1

[SD12] STELLMACH S., DACHSELT R.: Designing Gaze-based User Interfaces for Steering in Virtual Environments. In *Proc. of the ACM Symposium on Eye Tracking Research and Applications* (2012), pp. 131–138. 2

[SG06] SMITH J. D., GRAHAM T. C. N.: Use of Eye Movements for Video Game Control. In *Proc. of the ACM SIGCHI International Conference on Advances in Computer Entertainment Technology* (2006). 2

[SMSR17] SARGUNAM S. P., MOGHADAM K. R., SUHAIL M., RAGAN E. D.: Guided head rotation and amplified head rotation: Evaluating semi-natural travel and viewing techniques in virtual reality. In *Proc. of IEEE Virtual Reality* (March 2017), pp. 19–28. 1, 2

[SN93] SONG D., NORMAN M.: Nonlinear interactive motion control techniques for virtual space navigation. In *Proc. of IEEE Virtual Reality Annual International Symposium* (1993), pp. 111–117. 2

[UAW*99] USOH M., ARTHUR K., WHITTON M. C., BASTOS R., STEED A., SLATER M., BROOKS JR. F. P.: Walking > walking-in-place > flying, in virtual environments. In *Proc. of the 26th Annual Conference on Computer Graphics and Interactive Techniques* (1999), pp. 359–364. 1

[VKDB01] VIEILLEDENT S., KERLIRZIN Y., DALBERA S., BERTHOZ A.: Relationship between velocity and curvature of a human locomotor trajectory. *Neuroscience letters 305*, 1 (2001), 65–69. 4, 8

[WFGH11] WOBBROCK J. O., FINDLATER L., GERGLE D., HIGGINS J. J.: The aligned rank transform for nonparametric factorial analyses using only anova procedures. In *Proc. of the ACM SIGCHI conference on human factors in computing systems* (2011), pp. 143–146. 5

[WL11] WANG J., LINDEMAN R. W.: Isometric versus elastic surfboard interfaces for locomotion in virtual reality. In *Proc. of 6th IASTED International Conference on Human-Computer Interaction* (2011). 2

[WNR*07] WILLIAMS B., NARASIMHAM G., RUMP B., MCNAMARA T. P., CARR T. H., RIESER J., BODENHEIMER B.: Exploring Large Virtual Environments with an HMD when Physical Space is Limited. In *Proc. of the 4th ACM Symposium on Applied Perception in Graphics and Visualization* (2007), pp. 41–48. 6